Kelp Asset World Survey

Kelps are a group of conspicuous, large brown macroalgae in the Class Phaeophyta and Order Laminariales. Kelps commonly grow in areas ranging from temperate to subpolar regions, and do not naturally exist in waters warmer than 20 °C. Although not considered to be a diverse group with around 30 genera, their ecological importance cannot be understated. Kelps grow in large groups, ranging in size and density, however, the kelp beds of the giant kelp *Macrocystis pyrifera* can extend for many kilometers and be dense enough to act as a natural wave break, with individual thalli, analogous to the stems of plants, reaching up to 30 meters (Mondragon, 2003). The value of such an ecosystem service is difficult to calculate since its presence is so integral to the function of the diverse ecosystem that develops around it. Numerous species of fish, invertebrates, marine mammals, and other macroalgae utilize these ideal conditions.

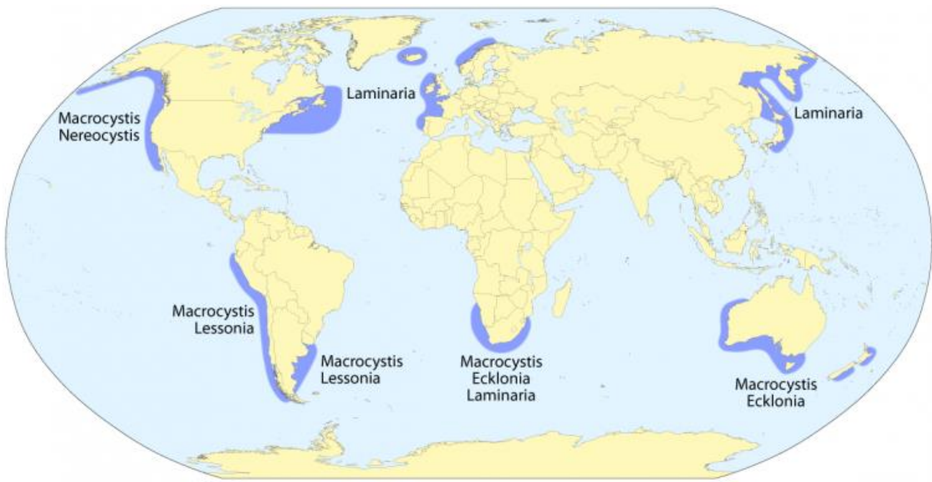


Figure 1: The global distribution of kelp species (highlighted in dark blue) with some of the primary genera that occupy those locations. Figure Credit: Maximilian Dörrbecker

Background

The historical uses of kelp are extensive. Some evidence shows that kelp and other seaweeds were dried and persevered by early humans in the Neolithic Era around 20,000 years ago (Dillehay et al., 2008). From existing historical records, it's shown that seaweeds were held in high regard in Japanese and Chinese cultures since only the ruling class could eat them. Around the year 3600 BC, the Chinese discovered that goiters could be treated by having the afflicted person ingest kelp (NCBI). Kelps are natural bioaccumlators of iodine, and can concentrate the essential mineral by 30,000x the concentration of the seawater in which they live (Zava & Zava, 2011). In Europe, kelps and other seaweeds were commonly used to feed livestock or spread onto fields to act as a natural fertilizer before commercial fertilizers were available.

Industrial uses for kelps did not develop till around the 16th century when it was discovered that seaweed could be burned to produce sodium salts (soda) and potassium salts (potash) and that kelps would produce the most soda and potash when compared to other seaweeds. The soda and potash that were obtained from the burning of kelps was used to produce glass, fertilizers, and eventually, gunpowder (Monterey Bay Aquarium). Elemental iodine was accidentally discovered in 1811 when a French chemist mixed kelp-derived potash with sulfuric acid, which produced a purple vapor and was recognized as a new substance and named iodine. Once the useful properties of iodine were discovered, such as its role as an antiseptic and as a treatment for goiter, iodine was produced from kelp potash at a commercial scale. When World War One began, Germany, who was the single largest producer of potash for fertilizer, placed an embargo on all exports of potash. This prompted the United States Government to begin to intensively research the kelp resources on its coasts which led to the commercial scale harvesting of the *Macrocystis* beds along the coast of California.

Although the harvest of various seaweeds and kelps has been taking place for thousands of years, the intentional farming of kelp is a fairly recent practice. *Saccharina japonica* was accidentally introduced to the shores of China in the early 20th century, but its presence was embraced and capitalized on. In Japan, kelp harvesters would throw rocks into the water around kelp beds, providing more substrate on which juvenile kelps could attach and grow on. The same practice was done around the introduced kelp thalli in China to firmly establish the species in the area. In the mid-20th century, the Chinese developed the methods by which *S. japonica* could be cultivated on a rope culture.

A great deal of research went into learning how to exploit their alternation of heteromorphic generations to harvest the large, blade-like diploid stage and use the microscopic haploid stage to seed the lines. While the industry was still in its infancy, strain selection was initiated to develop superior strains that would grow larger, and for a longer season, in order to increase their yields and extend the growing season to provide kelp for an extended time period. Today, China, Japan, Republic of Korea, and the Democratic Republic of Korea all use their own cultivars.

Cultivations methods have evolved as better products come onto the market. In the 50's, kelp seedlings were cultivated on ropes made of twisted palm or straw fibers and held afloat with sections of large diameter bamboo that acted as floats. The bamboo floats were replaced with glass floats, and palm ropes were replaced with nylon ropes. Today, plastic floats and nylon ropes are the standard in the industry. As the practices of kelp cultivation have spread around the world, the methods have not much changed. Largely, kelp is grown very similarly to the ways it is done in the main eastern Asian countries with long lines suspended from floats with weights on the grow out lines to keep the kelp at the appropriate depth for optimum growing conditions. The kelp is attached to the main grow out line via the smaller diameter seedstring, or the spores are directly seeded onto the main line. These modern methods have allowed for

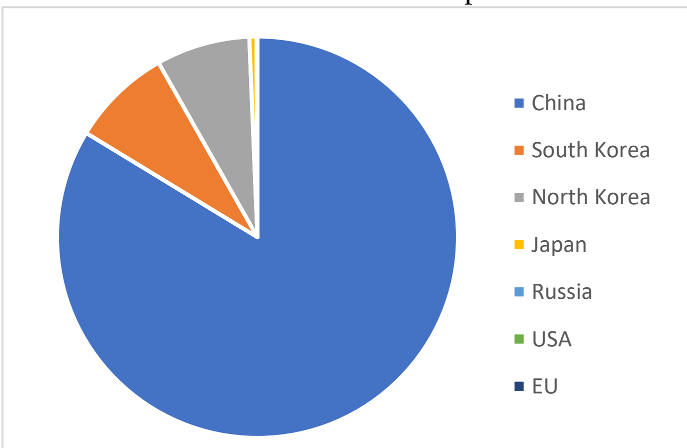


Figure 2: Chart of the major kelp producers in the world with their proportion of the global supply of kelp. Data is compiled for this study and sourced from FAO.

the rapid expansion of kelp industries in eastern Asian countries. The global industry is dominated by those four pivotal countries: China, South Korea, North Korea, and Japan.

Sometimes in China, kelp seedlings are reared in seawater until they reach a suitable length at which time, they are removed from the seed string and spliced into the main grow out line at appropriate intervals. This prevents overcrowding and produces larger thalli, since there is less competition for light and nutrients. This is especially true for kelp grown specifically for human consumption where a higher quality crop is needed. When kelp is grown for the hydrocolloid industry or for aquaculture feed for abalone or sea cucumbers, no thinning occurs because quality is less of a concern when compared to the need to maximize biomass production.

The uses for kelp are wide and varied. Kelp, especially *S. japonica* and *U. pinnatifida*, has been an important source of food for humans along coastal areas in Eastern Asia. Kombu, the common name for *S. japonica* and a few other related species which originated in Japan, was an important trading commodity that would make its way to the interior of China and eaten as winter vegetable. It's high vitamin and mineral content made it an important source of nutrients in times when fresh vegetables were impossible to access. The reason *S. japonica* cultivation was so heavily invested in initially was that a significant proportion of Chinese citizens were afflicted with goiters due to iodine deficiency. As such, the government encouraged the cultivation of *S. japonica* to make the kelp widely available to improve the health of the country's inhabitants.

(NASA Earth Observatory image by Jesse Allen, using Landsat data from the U.S. Geological Survey.)

Figure 3: Aerial photograph of Sisan Island, South Korea and the kelp farms that surround it. Expansive networks of lines covering thousands of hectares are common sights along the productive coasts of China, the Korean Peninsula, and Japan. For scale, the large island is 4.83 km long.

Today, kelp is still a valuable commodity. Kombu is sold for around $2800 per tonne (dried), and *Undaria* or wakame is sold for around $6900 per tonne (dried) (McHugh, 2003). In western countries where *Saccharina latissima* and *Alaria esculenta* are the cultivated species, prices differ. In Norway, *S. latissima* sells for about $399 per ton and *A. esculenta* sells for about $1099 per ton (wet weight) (Stévant et al., 2017). Although the prices appear to be significantly different, the discrepancy arises in the presence or absence of water, or wet weight vs dry weight. In reality, western kelp sells for more money than the mass-produced kelps grown in eastern Asia. Differences in prices can vary significantly due to applications and availability. The large difference in prices between *A. esculenta* and *S. latissima* is thought to be in part due to the lack of *A. esculenta* on the market, making it more of a specialty product. Additionally, *S. latissima* has a broader range of applications on the market.

Specific information is often difficult to come by, and the reasons for this vary by regions. In the West, the kelp industries are very young. Research is still ongoing regarding which methods are needed for kelp to be grown successfully. Many farms are little more than experiments or trial runs to investigate the plausibility of a larger scale operation, and for that reason, the data for sizes or harvest amounts are nonexistent at times. In other places, the industry is not as valuable as other fisheries or enterprises that are managed within a given agency, and for that reason, the data for the number, size, and production values are not readily available, simply because no one has taken the time to look. In these areas, someone with knowledge and connections in each area would be needed to make contact with individual companies or growers in order to compile a comprehensive view of the kelp industry for that specific industry.

In the Asian countries where the kelp industry is well established, specific information regarding the sizes, locations, and operators of kelp farms is not readily available either. South Korea seems to have the most academic papers available regarding their industry, but most information is about selective breeding practices or overall production. China's kelp industry is by far the most substantial, as they produce more kelp than the rest of the world combined. However, specific information regarding their farming practices is lacking. Similarly, intentional effort would need to be invested to each country's industry in order to gain a better understanding of the specifics of each region. A great deal of effort and integral connections would be necessary to elucidate the intricacies of the substantial industry in eastern Asian countries.

China

History

China was producing kelp pre-1950 by relying on wild stocks and patches of kelp that were tended to much like garden plots. Their production peaked in 1949 with a total mass of approximately 40.3 tons dry weight. The floating rope or raft culturing methods were being developed the following two years, allowing for 114.7 tons to be harvested in 1953. By 1958, China was producing 6,253.3 tons of kelp, an increase of more than 154 times the production in just a span of 8 years (Zeng (Tseng) 1984). The development of these methods of seeding onto an artificial substratum set the stage for the industry in China to scale up the production of kelp extremely rapidly. As seen in Figure 2 below, production levels have continued to grow rapidly, and today, China produces most of the kelp in the world.

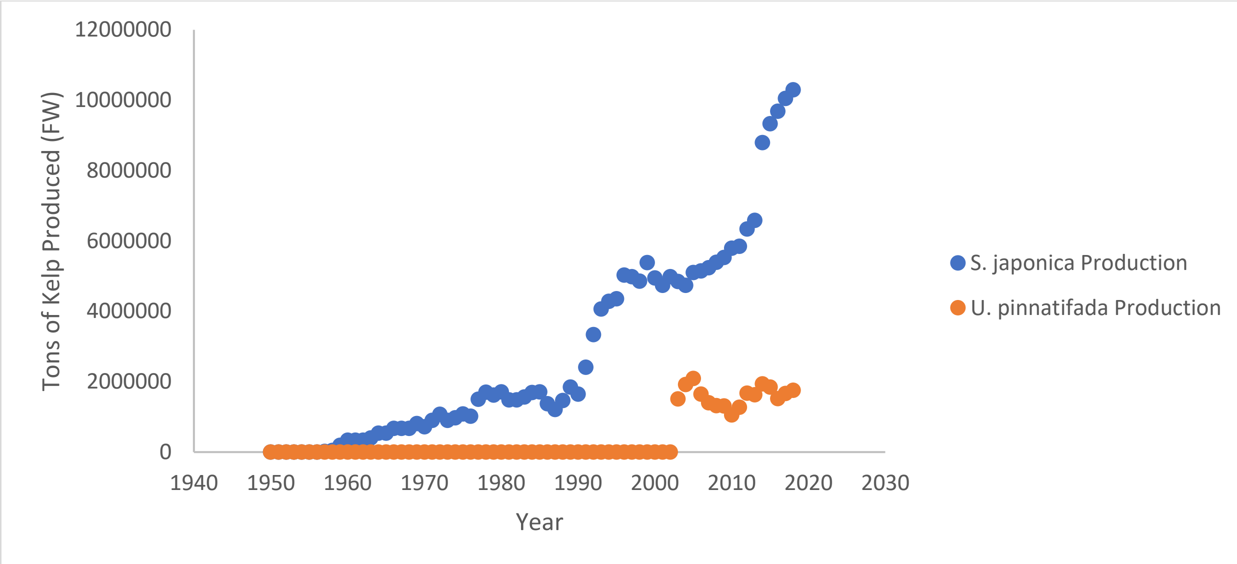


Figure 4: China's production of *S. japonica* and *U. pinnatifida*. Combinations of numerous factors have allowed the production seen today, but the development of rope culture and genetic strain selection are arguably most responsible for the increases in production.
Data from FAO.

Environmental Conditions

China has a long coastline that ranges between latitudes 18° N and 54° N, meaning that the climate changes significantly as one surveys across these latitudes. The northern areas that border Siberia are subboreal, whereas the southern latitudes are quite warm and tropical. This significant transition of temperatures creates variation in the algal species that naturally occur along the coast of China. Kelp species prefer colder water, as is found in China's more northern providences such as Shandong and Liaoning, where water temperatures stay within kelp's optimal temperatures of 5-10 °C. However, experiments in 1956 showed that sufficient growth could still occur in water temperatures above 10 °C, and as such, industrial cultivation of *Undaria* and *Saccharina* species spread to China's warmer Southern providences of Zhejiang, Fujian, and Guangdong.

Methods

The methods developed for the seeding of kelp onto an artificial substratum are scalable, meaning that a farmer could have a series of lines that occupy less than a single hectare, or, as seen today, a major company could have a series of lines and floats that covers more than 6,700 hectares (Zhang, 2015). This ability to adjust the efforts invested based upon the space available has allowed kelp farming practices to spread across much of China's eastern coast. The practices were initiated in the northern providence of Liaoning in the city of Dalian. Farms quickly spread to the providences of Shandong and Jiangsu, as both of these providences have water temperatures in the optimum growing range for the kelp, between 5 and 10 °C. Kelp farming in China is a large enterprise, and this is a significant range in the effort invested by each company or farmer. Farms as large as 6,000 hectares are major corporations, which represents the majority of the kelp farming effort seen in China. These company farms generally range in sizes between 3,000 and 6,700 hectares and are described as being situated in offshore, open sea areas. These expansive farms rely on seasonal workers to do the outplanting in the fall and the harvesting in the late spring and early summer. Although large farms do represent the majority of kelp farming efforts, the sizes of farms, and the effort that is invested in them does vary. In the northern providences of Shandong and Liaoning, large company farms dominate the available areas. But in the southern providences, especially Fujian, smaller family operations still exist, deploying and maintaining lines that occupy a few hundred hectares (Zhang, 2015). No major differences in the size or amount of effort exists between farms dedicated to farming different species of kelp.

Although the southern providences of Zhejiang and Fujian have warmer water temperatures outside of that optimum range, experiments were soon taking place to determine whether Japanese kelp, or kombu, could be grown at a commercial scale. With water temperatures sometimes reaching 20 °C and the very turbid water, expectations were low. The results of the experiments eventually did show that a sufficient biomass could still be grown, even though the warmer water temperatures cut the growing season significantly shorter than those seen in the northern providences. The solution to adapting to the turbid water was to simply raise the grow out lines closer to the surface of the water. Once the Zhejiang and Fujian providences were deemed suitable for kelp cultivation, large scale farms were soon established there. These farms continue to produce a significant proportion of China's kelp harvest. The expansion of kelp farming in Fujian and Guangdong is closely associated with the expansion of abalone aquaculture (Hwang et al., 2019). Abalone farming has been rapidly expanding in the last several years, and abalone need to be fed fresh feed, and much of that is provided through the widespread cultivation of S*accharina* and *Undaria* species. Farms in these southern regions do provide a significant portion of the all the kelp grown in China, but many smaller farms operate in this region. Many of the farms are associated with other larger aquaculture operations to provide feed for other components of monoculture or IMTA facilities.

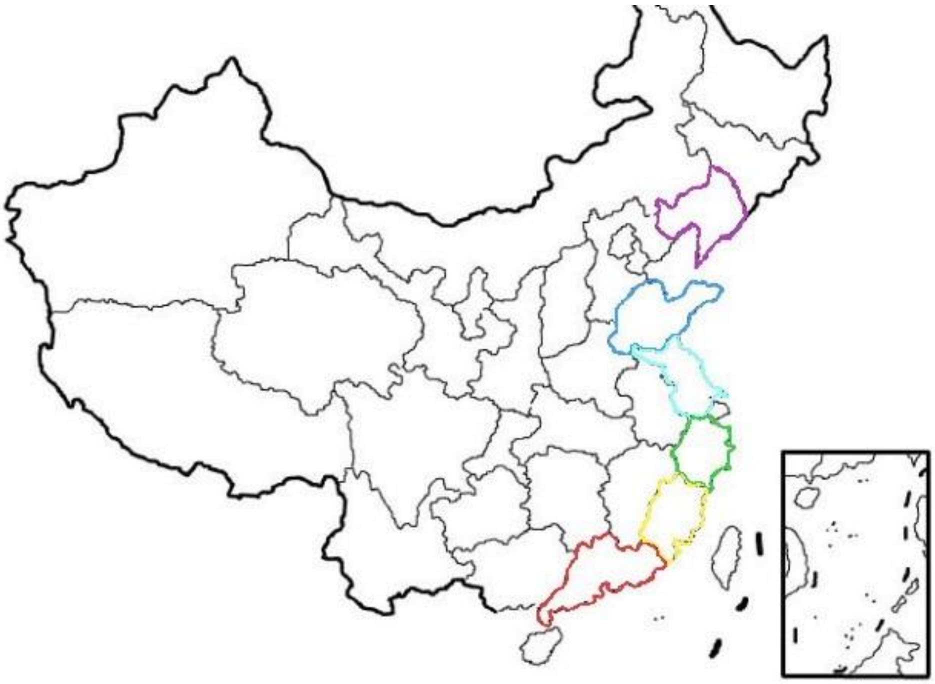
Cultivar Development

China's cultivar breeding program originated early in the kelp industry's development. An ideal cultivar can be bred for different purposes. Nearly always, disease resistance is required, as there are numerous bacterial and pathogenic diseases that can severely impact a kelp farm's yield (Fang, 1983). Since yields need to be maximized, individuals are grown tightly together, making entire crops susceptible to outbreaks of disease. Aside from that, cultivars can be bred to increase yields by maximizing length or thickness of the blade, or they can be bred to have better nutritional quality by having higher vitamin and mineral contents. When iodine was more intensively produced from kelp, a cultivar was bred to improve the levels of iodine that was concentrated with in the kelp tissue. Beginning in 1970, scientists began crossing and breeding *S. japonica* thalli from across all the providences. While the thalli were maturing, the distal portion of the blade was cut off and tested for iodine levels. The remaining portion of the thalli continued to mature. Using the results from the iodine analysis and growth measurements, individuals were selected for increased growth rates and high iodine contents. The study resulted in two strains that result in larger biomasses and higher iodine contents. Later a hybrid was created by crossing the two strains which reportedly had higher yields than either of the parent strains (Fang, 1983). The targeted market will generally dictate which cultivar a farmer will use on their farm. Strains exhibiting higher concentrations of hydrocolloids are better suited for the alginate industry, whereas kelp for human food needs to have superior nutritional qualities and would place a higher priority on appearance.

Many cultivars have been developed in China over the several decades as the industry has progressed. The various strains have been created by individual farms, industries, or researchers (Pang et al. 2015). However, only ten have been officially registered with the Chinese Ministry of Agriculture. Of the ten cultivars that have been registered, there are three types. Type one is created by interspecific crossing, meaning that two different cultivars are crossed (Zhang et al., 2011). Type two is created by crossing *S. japonica* with an individual of *S. longissima*, and then crossing the hybrid offspring with another *S. japonica* (Li et al., 2008). Finally, type three is created by crossing individuals of *S. japonica* that have been geographically isolated (Li et al., 2016). The whole process is tedious and requires careful tracking of gametophyte parents and corresponding sporophyte offspring. It generally takes six years or more for the strain to stabilize on the desirable characteristics (Hwang et al., 2019).

Undaria pinnatifida is the other important kelp species undergoing active cultivation in China. China does have native populations of *U. pinnatifida* and has been growing the species since the 1950's. The strains that are grown in the main kelp growing providences are believed to have been introduced from Japan, who represents China's main export market (Hwang et al., 2019). Japanese buyers had rigid requirements on the products they were willing to buy, so Japanese strains were introduced to Chinese farms in order to satisfy those requirements. Today, China has two registered strains of *U. pinnatifida* that have developed in their country. The two cultivars were developed such that one strain matures earlier than the other. This gives enough time in the harvesting season to completely harvest and process the early maturing strain before beginning to harvest the later maturing strain. The staggered harvest times also provide fresh product to consumers for a longer amount of time.

Kelp Producing Providences of China



Provinces	***S. japonica*** (tons dw)	***U. pinnatifida*** (tons dw)
Liaoning	218,704	106,855
Shandong	533,439	43,961
Jiangsu	300	4
Zhejiang	10,363	–
Fujian	693,533	–
Guangdong	4719	1029

Table 1: Production values for each *S. japonica* and *U. pinnatifida* producing providence in China. Each color corresponds with its placement on the map above. Cooler colors correspond with cooler water temperatures. Data from Hwang et al., 2019.

The Korean Peninsula

History

The two nations on the Korean Peninsula both actively produce kelp at an industrial level. Although more information is available regarding South Korea's history on the subject, both countries primarily produce *S. japonica* and *U. pinnatifida*. *U. pinnatifida* occurs naturally all along the coastlines of the peninsula and has been cultured commercially for several decades. *S. japonica* was introduced to the area from Japan in the 1970's.

In South Korea, both species are grown extensively for human food, as well as for abalone feed, although a cultural preference for *Undaria* exists for human consumption. The total production for both species represents more than 1.1 million tons of biomass, roughly two thirds of all seaweed produced in South Korea. South Korea is different from China in that they grow more *U. pinnatifida* than *S. japonica*. In 2018, 622,613 tons (fresh weight) of *Undaria* was grown, whereas only 542,285 tons of *Saccharina* was grown (Ministry of Oceans & Fisheries. 2018). South Koreans have traditionally consumed more *Undaria* than *Saccharina*, so that could explain the difference in cultivation efforts. Upwards of 90% of all the kelp grown in South Korea is grown along its southwestern coast in the providence of Jeollanam and the surrounding area (Sohn, 1998).

S. japonica was actively farmed at a much smaller scale in South Korea until the abalone industry began to expand in a significant way, beginning in the early 2000's. Since then, cultivation efforts have multiplied by several times, and now, more than 9,000 hectares are dedicated to farming *S. japonica* for both human food, and more importantly, for abalone feed (Hwang et al., 2019). The autumn sporeling-rearing technique was pivotal for developing a cultivar that would suit the needs of the abalone farmers (Sohn, 1998). The normal life cycle of kelp generally has the growing season in the winter, and by early summer the blades are badly deteriorated and not suitable for use as food or feed. The autumn sporeling-rearing technique postpones the sporing out process in the early fall until several weeks later. This delay extends the growing season into the early summer and allows the kelp to be harvested much later and provides feed for the abalone farmers into the summer months when feed is more difficult to come by.

Environmental Conditions

Water temperatures vary along the Korean Peninsula and are influenced mainly by two currents. The North Korean Cold Current branches off the Liman Cold Current and runs along the west coast of the peninsula, which lowers the average water temperatures in the northern regions of the Korean Peninsula. In the winter, the minimum temperatures hover around 2-3 °C, but temperatures can exceed 25 °C during the summer in some areas. The peninsula as a whole is more influenced by the Kuroshio Warm Current that flows up from the south (Sohn, 1998).

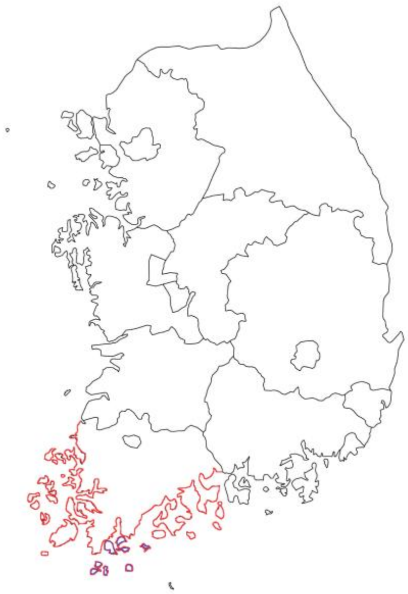


Figure 5: Map of South Korea's main kelp producing region, the providence of Jeollanam (outlined in red). Wando County (outlined in blue) is especially central to South Korea's kelp and abalone industry.

Cultivar Development

Extending the growing season even further is one of the main priorities in the breeding program in South Korea. As of 2018, there have been 5 cultivars of *Undaria* and one of *Saccharina* that have been registered for variety protection. These cultivars have been developed with either hybridization or consecutive selection. For example, Hwang et al., 2012 examined the growth of a hybrid of *U. pinnatifata* and *U. peterseniana* and found that it had better growth and performance than either of its parent species.

The Food and Agricultural Organization of the United Nations reports North Korea produced an estimated 572,600 tons of *S. japonica* and 515,600 tons of *U. pinnatifida* in 2018 (FAO, 2018). That is all the information available regarding the kelp industry in North Korea.

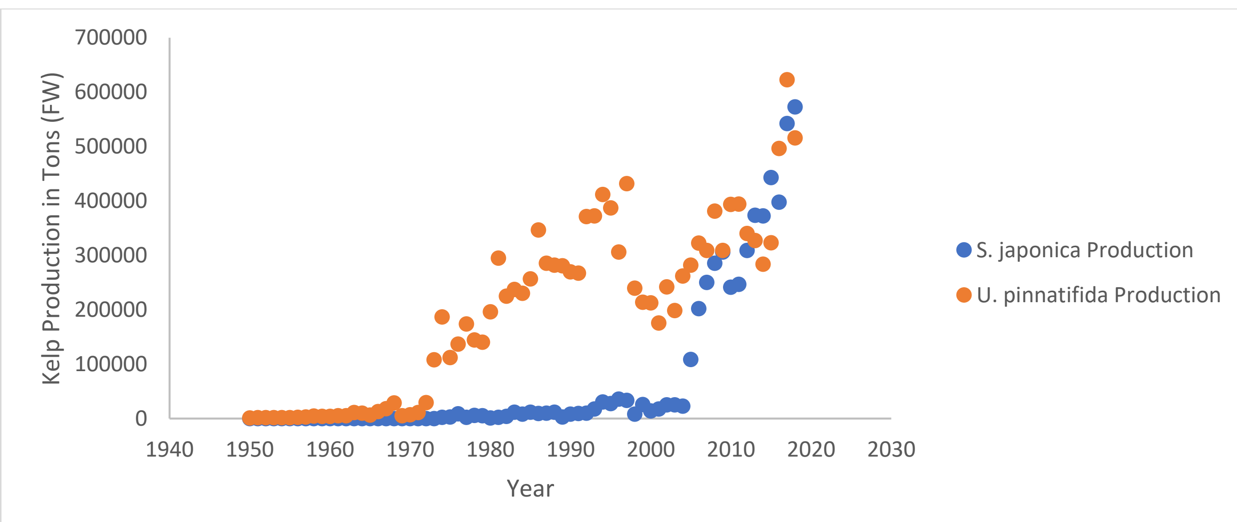


Figure 6: Kelp production in South Korea from 1950 to present. Data from FAO.

Japan

History

Japan has been harvesting their wild kelp bed resources for hundreds of years, but intensive farming of *S. japonica* did not begin until 1969. The farming began because the natural kelp beds were in decline and could no longer produce enough biomass to adequately supply the industry (Kawashima, 1984). However, *Undaria* had been farmed commercially for several years prior to 1969. Production for *Undaria* began to sharply increase in the mid-1960's and continued to increase into the 70's. Production plateaued for several years but has since continued to decline into the present. *Saccharina* cultivation saw steep increases to production following its initiation in 1969. It saw its highest levels of production in early 1990's, but since then it has slowly but steadily declined into its current production levels. In 2018, Japan produced 33,300 tons of *S. japonica* and 49,800 tons of *U. pinnatifida* (FAO, 2018).

Figure 7: Kelp producing prefectures of Japan. From North to South: Hokkaido, Miyagi, Iwate, and Tokushima.

Environmental Conditions

The country of Japan is made up of a unique archipelago of four main islands of Hokkaido, Honshu, Shikoku, and Kyushu (northernmost to southernmost) and an additional 4,000 more smaller islands among them. Their environment and water temperatures are strongly influenced by the water currents that move around the islands. The Oyashio current flows to Japan from the North and brings very cold water out of the Arctic, keeping the water around Hokkaido very temperate with average temperatures of 16-18 °C in the summer and as low as -1 °C in the winter (Ohno and Largo, 1998). This cold-water current creates suitable conditions for kelp growth in Northern Japan.

Uses

The majority of kelp grown in Japan is consumed within the country. Japan consumes the largest amount of seaweed per capita, which has been linked by some to their overall good health and longevity. Japan does not grow enough kelp to completely supply itself with enough kelp, significant volumes are imported from both China and South Korea.

Japan also produces alginate, although cultivated S. japonica and U. pinnatifida are generally too expensive to use as a raw material for that application. The alginate that is produced in Japan is sourced from raw materials that are imported from mostly Chile and South Africa, who harvest wild Durvillea and Ecklonia for export (Ohno and Largo, 1998).

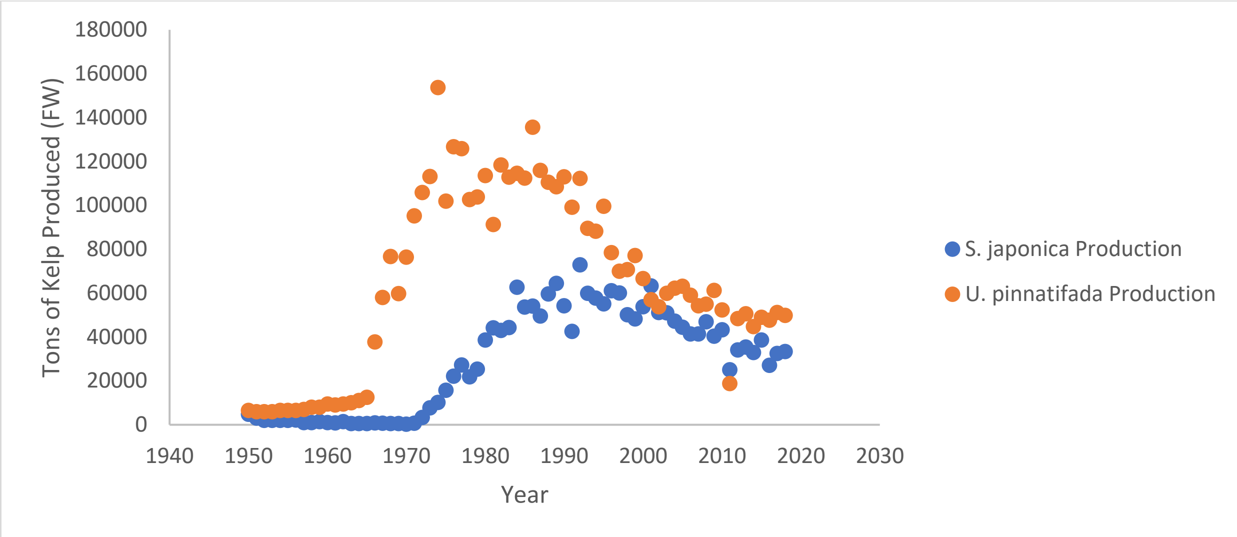


Figure 8: Kelp production in Japan from 1950 to present. Data from FAO.

Europe

History

The European Union has a long history of exploiting its natural resources in the ocean, especially with activities like capture fisheries for finfish and shellfish, and there is a burgeoning interest in aquaculture. Aquaculture practices for growing salmon and trout are well established in the Northern EU, in countries like Sweden, Scotland, and France, and interest in kelp aquaculture is growing as well, with the species *Saccharina latissima* being the main target for cultivation, as studies have shown its potential for generating large biomasses (Handå et al., 2013) Several countries also have long histories with exploiting wild stands of kelp, usually for industrial applications.

Norway

Norway has been harvesting its natural kelp beds for around fifty years (Stévant et al., 2017). Norwegians were quick to recognize the value of their fast growing and renewable resources along the coastline and were among the first countries to establish harvesting guidelines and criteria to maintain ecosystem diversity. The main kelp species harvested is *Laminaria hyperborea*, and it is harvested from specialized boats using trawling equipment that removes the kelp's holdfast from their rocky substrate. The regulations and management of the wild harvest of Norwegian kelp beds is considered to be among the most thorough in the world. Harvest limits are set for each area, and once a bed has been harvested, a minimum of four-year waiting period is required before the area can be harvested again. This allows the kelp bed to regenerate, and for the ecosystem it supports to restabilize.

In 2019, Norway harvested just less than 163,000 tons of brown algae, most of which was *Laminaria hyperborea* or *Laminaria digitata* (Norwegian Directorate of Fisheries). Most of this harvest is processed for hydrocolloid extraction (alginates). Although wild harvest of kelps has been well established for many years, it became apparent that wild harvest would soon no longer be able to support the demand for kelp biomass. To avoid the overharvesting of algal resources like seen in France and Morocco, alternative sources had to be evaluated. Experimental farms were deployed in 2005 to determine the feasibility of kelp aquaculture in Norway. Due to its established finfish aquaculture systems and the resulting nutrient discharge from waste and uneaten food, kelp aquaculture seemed to be a logical answer to address the problems of eutrophication and generate a valuable biomass simultaneously (Wang et al., 2012).

Commercial kelp farming permits were first issued in 2014 once the government established a temporary permitting process to certify commercial applicants (Stévant et al., 2017). The number of permits granted has been on the rise ever since 2014, and the Norwegian government has been allocating larger areas for macroalgae farming. In 2014, 54 licenses were granted for kelp farming, and that number has risen to 475 in 2019 (Norwegian Directorate of Fisheries). Many of these farms are in start up phases, and production values will continue to grow as more companies actively grow kelp on their permitted sites.

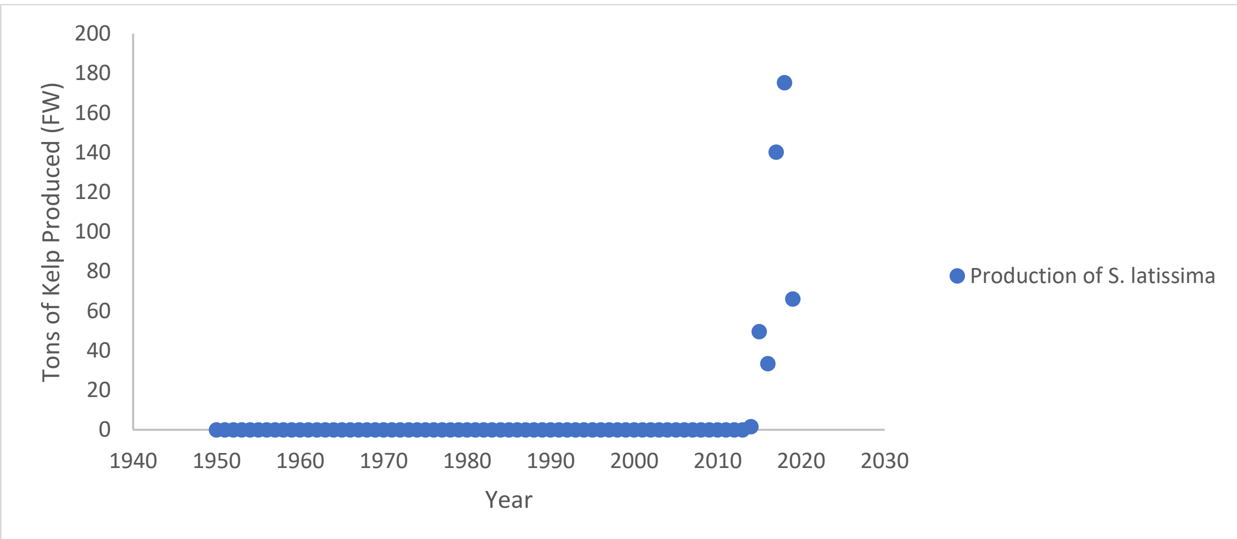


Figure 9: Kelp production in Norway. Everything before 2014 is a zero. Although Norway has a strong history of wild harvest, kelp aquaculture is a very recent endeavor. Permits have been granted for the farming of *L. digitata* as well, but it has not yet been harvested in significant volumes.

In the European Union, interest in kelp cultivation continues to grow, just as it is in Norway. Even prior to Norway's exploration into *S. latissima* cultivation, several other countries in the EU had conducted their own experiments and obtained promising results, including France, Germany, Scotland, and Ireland (Stévant et al., 2017). The list of countries in the EU that are actively researching the possibilities of growing kelps at industrial scales continues to grow. Today, Sweden, the Netherlands, Denmark, and Great Britain all have kelp farming companies in their economic zones. Although kelp is being grown in these locations, they are still operating at a small scale and represent a very small faction of a percent relative to the global production scale. The website www.phyconomy.net provides opensource data on the numerous companies and enterprises involved in the growing, harvesting, processing, and marketing of kelp and other algal species around the world, but especially Europe. This represents a valuable resource when evaluating the investment European countries are making to work towards a more environmentally-focused economy and future.

France

It is worth noting that France has a long history wild harvest. It has a well-established fishery that targets wild kelp beds of *L. hyperborea* and, to a greater extent, *L. digitata*. Mechanical harvest from large vessels began in the late 1960's when the "scoubidou" was developed. The scoubidou is a large iron hook attached to the arm of a crane and is used to twist up the thalli of mainly *L. digitata*. *L. hyperborea* is harvested from boats with a large rake that is pulled through kelp beds, which pulls up the holdfasts. The kelp is then sent to factories where it is processed for alginate extraction by Dupont-Danisco and Lannilis for Cargill (Mesnildrey, et al., 2012). Between 40,000 and 60,000 tons of *L. digitata* and around 11,000 tons of *L. hyperborea* is harvested each year (Mesnildrey, et al., 2012).

In addition to their wild harvest landings, France also produces approximately 50 tons of kelp on aquaculture facilities. *S. latissima* and *U. pinnatifida* are both farmed. There are only seven farms, four in North Brittany, two in South Brittany, and one in Vendée (Mesnildrey, et al., 2012). However, France is at the forefront of research efforts to develop new uses and applications for cultured kelp. For example, the company C-Weed Aquaculture has its own culture and processing facilities and develops a wide range of products. In addition, all their products have Bureau Veritas (FR BIO 10) organic certification (Ferdouse et al., 2018). Both companies work to find new uses and presentations for incorporating kelp into western diets and lifestyles.

Innovations

Innovation is continually pursued as markets and products are developed and promoted, and technology is designed and implemented to make industrial scale kelp production a competitive practice in the European Union. MACROSEA, a program run by SINTIF in Norway, is acting as a common area for everything pertaining to industrial scale cultivation of kelp. Research is conducted in every step of the process, including seed quality, sea cultivation, and genetic studies, as well as 3-D modeling efforts to optimize kelp farming practices (MACROSEA, www.sintef.no/projectweb/macrosea/, Broch et al., 2019). Several technologies have been tested to evaluate their effectiveness to keep kelp farming equipment intact in offshore locations. The advantages to growing kelp offshore are many and are mostly represented by a decrease in user conflicts and an abundance of unoccupied space. Grandorf et al., 2018 tested the Macroalgae Cultivation Rig (MACR) and showed that it effectively held the kelp cultivation equipment in place even when subjugated to offshore waves. A method was also evaluated the effect of doing multiple partial harvesting on the overall cost of production. By doing four partial harvestings over a two-year period, the cost of production per kg of kelp was reduced from € 36.73 to € 9.27 (Grandorf et al., 2018). Seaweed Solutions (formally Seaweed Energy Solutions) has patented a method of cultivating kelp on set up known as

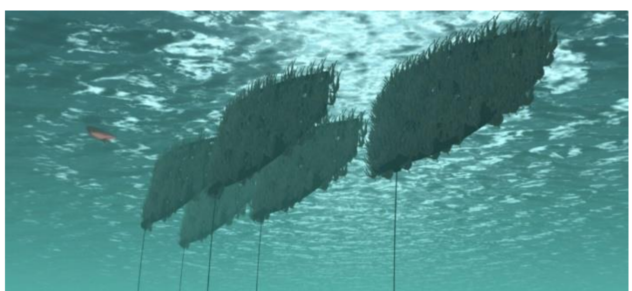


Figure 10: The Seaweed Carrier, patented by Seaweed Solutions.

the Seaweed Carrier. The Seaweed Carrier is designed to be deployed in offshore environments. Its construction is similar to that of a kelp thallus, with a single “holdfast” anchor connected to the floating cultivation site via a single cable. This construction should allow for enough movement in order to remain stable during extreme weather events and prevent catastrophic losses (www.seaweedsolutions.com).

Creating technologies that increase production and improve efficiencies will be imperative to the successful implementation of industrial scale production of kelp in Europe.

United States of America

History

The kelp industry in the United States of America (USA) is still in its infancy. The first kelp farm was founded in Casco Bay, Maine in 2010 (Flavin et al, 2013). The cofounders wrote a book called the “Kelp Farming Manual: A Guide to the Processes, Techniques, and Equipment for Farming Kelp in New England Waters” that continues to be an invaluable resource for American kelp farmers that are getting started in the industry. Although interest is growing in a few areas, production levels are still relatively small, and the infrastructure required to do anything with the generated biomass has yet to be sufficiently developed. Harvesting aquatic species from the wild has an extensive history in North America, involving both algal species, as well as finfish and shellfish. However, relative to other countries, the extensive coastline has been underutilized in regard to aquaculture efforts. The USA continues to be the top importer of fishery related products, and the fifth largest exporter of fishery products. Production values for both wild harvest and aquaculture efforts have remained stable for the last several years. The production of any aquatic plants is not included in the official statistics from the FAO, demonstrating how minute current production levels are (FAO, 2019).

Although efforts are currently limited, interest continues to grow. Currently, kelp is being grown at either a commercial or a research level in the following states: Maine, New Hampshire, Connecticut, Rhode Island, Massachusetts, New York, Washington, and Alaska.

Challenges

When compared to the kelp industries of Eastern Asia, kelp farms in the USA are miniscule. Kelp farms in the USA undergo an extensive permitting process that often requires permits from several agencies. Issues involving competition from other stakeholders in the farm area often creates significant push back from the community. Additionally, finding markets for the harvested biomass once a farm has been established also represents a challenge, making profitability difficult to achieve. These challenges make it more difficult for the kelp industry in the USA to grow and expand into something to be recognized at the global scale.

In terms of regulations, there is much concern surrounding the potential to damage the surrounding ecosystems that kelp farms are placed into. Much of the permitting process involves doing risk assessments to other species or ecosystems of concern, such as eel grass beds (*Zostera marina*). Another significant concern is contaminating the gene pools of wild kelp beds. Several studies from East Asian countries already have found evidence of gene flow between wild and farmed kelp that occupy similar spaces. Due to kelp’s reproductive strategies, individual spores are able to be carried by currents, greatly increasing their dispersal potential. Alaska Department of Fish and Game has written the regulations for sourcing parent plants to prevent the contamination of wild gene pools. ADFG dictates that 50-60 parent plants sourced from the wild must be used to seed the lines that are out planted onto a farm. It is expected that this farmed diversity should help maintain the total diversity present in the environment.

Maine and Alaska

Most of the kelp grown in the USA is grown in Maine and Alaska. Both of these states have extensive coastlines, as well as existing infrastructure related to extracting marine resources. Having a population that is familiar with working on the water is important for the establishment of a kelp farm and having an abundance of coastline decreases concerns regarding user conflicts. In both states, more permits are being issued, and existing operations are expanding.

The main kelp species of interest in the USA is *S. latissima*, and it is grown on both the East and West Coast. On the East Coast, *Saccharina angustata, Alaria marginata, and Laminaria digitata* are also cultivated. Until recently, *S. angustata* was considered to be a unique variety of *S. latissima* because the blade is much more narrow, however, enough genetic differences were found to consider it its own distinct species. On the West Coast in addition to *S. latissima*, *Nereocystis luetkeana* and *Alaria marginata* are also cultivated in large quantities.

Although Alaska does not allow for the use of intensively breed strains of kelp, the ARAP-E program from the US Department of Energy has awarded Woods Hole Oceanographic Institute a grant to continue a selective breeding program to develop superior strains of kelp that can be grown in US waters (ARAP-E, 2017). In order to grow a biomass large enough to create an adequate supply for biofuel applications, a number of aspects of entire production chain will need to be optimized, including the genetics of kelp that will be grown, thus maximizing the yield per unit of effort invested. Other grants from the ARAP-E Mariner program have been awarded for the research into other aspects of kelp product in US waters. This strong investment from the government and changing the publics views on kelp will help ensure that the US kelp industry continues to grow and becomes a profitable component of the USA's economy and future.

Kelp Processing and Uses

As aforementioned, kelp was first exploited for industrial purposes as a source of potash used glass production, beginning in the 17th Century (Mesnildrey, et al., 2012). Prior to that, kelps have been used as a source of food and other herbal remedies in Eastern countries for millennia. Food for humans does represent the most common use for farmed kelp, but the processing that is required to convert raw kelp into a marketable product can vary significantly.

There are a few aspects to kelp that must be considered when developing protocols for the processing of kelp. Since all kelp species are aquatic, the vast majority of their biomass is water, ranging from 70-90% (Jensen, 1993). This poses potential problems for both the logistics of transporting large volumes of biomass, as well as for processing large quantities of kelp for their valuable elements. Additionally, fresh kelp biomass quickly begins to microbially decompose, which also poses problems for the logistics of processing kelp (Enríquez et al., 1993). Drying kelp halts that microbial decomposition, but that can also alter the nutritional qualities of the kelp (Gupta et al., 2011). Processing techniques must be tailored to obtain the desired outcome for each specific end product. Intuitively, kelp that is allocated for human food will be treated differently than kelp allocated for hydrocolloid extraction.

Kelp for Human Food

Kelp allocated for human food will go down a series of steps to arrive at a safe, marketable product. Traditionally, kelp was either consumed raw or in a sun-dried form. Kelp can still be purchased raw in a fish market or similar environment during the seasons that the kelp is being harvested, and sun drying kelp is still an extremely common practice. When dealing with the astounding volumes of kelp that are harvested in China, Korea, and Japan, a variety of methods must be employed to utilize the maximum proportion of the biomass harvested before it degrades. In very large operations, multiple strains of a species with varying maturation rates will be out planted. The staggered timing of maturation gives harvesters the opportunity to stagger the harvest, instead of having the whole crop reach maturation simultaneously.

After the kelp is harvested, it is transported to a processing facility, with the exception of kelp that is to be dried. Sun drying kelp is still a common practice China, Korea, and Japan. Kelp is laid out on the beach, in unoccupied agriculture fields, or on long racks made of bamboo or steel specially built for kelp drying. Debris can stick to the kelp when it is laid on the ground, and the extent of the contamination will impact its value. Dried kelp is widely available as a food product. It can be sold in large pieces for a wholesale market or cut down into smaller manageable pieces that are more common for products directly marketed to single households. Sometimes, dried kelp is shredded to a consistency similar to tea leaves, which are then used to brew a hot beverage in a similar fashion to tea. Dried kelp can also act as a feedstock for alginate extraction. In South Korea, dried *Undaria* is widely available, and is often included in many processed food, snack, and well-being products to utilize *Undaria's* natural nutritional value (Hwang and Park, 2020).

Kelp for human food will undergo a pretreatment process that involves a series of seawater or freshwater rinses to remove debris and salt content, respectively. The next step in the pretreatment process is to either blanch it or boil it. Cooking the kelp effectively stabilizes it, and extends it shelf life. For some products, a green dye is added to the boiled kelp, turning it a vibrate green color, and that would occur right after the boiling process. Once the kelp is boiled, it is salted and placed in cold storage to await its transfer to a food processor.

Processing Equipment

Once pretreated kelp arrives at a seafood processing factory, it can be transformed into any number of food products including: dried, semi-dried, wet, salted, non-salted, seasoning products, sliced, tied, kelp sauce, kelp noodles, or kelp soup-mate (Zhang, 2018). The packaging that the final product ends up in can vary in sizes and shapes. Machines involved in the processing of kelp products include, but are not limited to, washing tanks or tunnels, kitchen cookers or blanchers, dewatering machines, cutting/slicing machines, drying tunnels, cooling fans, heavy metal sensors, scales, packing machines, vacuum packing machines, and many other types of equipment. Heavy metal detectors are especially important when processing kelp that may have been grown in waters polluted by anthropogenic activities. Processing lines must be specialized for the product that is being produced, and often times, specialized equipment must be custom built in order to produce a novel product.

Kelp for Industrial Uses and Feed

Kelp that is not being used for human food can then go towards two broad categories: industrial uses and animal feed. For animal feed, the processing necessary will vary depending on what animal it will be fed to. In China and Korea especially, kelp represents a significant source of feed for abalone and sea cucumber farms. For this application, little to no processing is required, as pieces of fresh kelp are simply placed in the cages with the animals at regular intervals. Growing *S. japonica* exclusively for use as abalone feed caused the area utilized for *S. japonica* in South Korea to increase by 671% between 2001 and 2015, and now occupies 9,147 hectares (Hwang et al., 2019). This simple example demonstrates the importance that this application holds in the industry.

Kelp is a common component of other kinds of animal feeds, such as feed for higher trophic levels in aquaculture like finfish or crustaceans. For these applications, the kelp is generally dried and then pulverized into a powder that can then be added to the other ingredients. Kelp can serve as a source of plant-derived protein, which will become more and more important as the world's population grows and there are more people to feed. *U. pinnatifida* can be around 16.3% crude protein, with S. japonica and L. digitata containing roughly 6.2% crude protein (Misurcova, 2011). Using animal protein in animal feeds is sometimes viewed as using food to make food. Using algae-based proteins circumvents that problem by utilizing protein from lower trophic levels. The generation of algae-based proteins is also attractive because no freshwater or farmland is used. Many other plant-based proteins are derived from soy, which returns to the problem of using food to grow food. However, the protein content is not the only reason using kelp in animal feeds is useful, due to the micro- and macronutrients found in kelp tissue. Supplementing normal feed with kelp is common in the organic farming sector, which significantly reduces the additives that can be administered to farm animals. Some studies have seen improvements to body condition and overall health in both pigs and cattle when kelp is added to their diet.

Hydrocolloid Extraction

The industrial uses for kelp are broad, and there are ongoing research efforts to discover more uses for the bioactives that are contained in kelp tissue. The hydrocolloid industry has been a dominant component in the kelp industry since alginate was discovered and has had its useful properties applied to its myriad of applications. Alginate, or alginic acid, is a structural component of all the seaweeds in the Phylum Phaeophyceae and is the most widely produced polysaccharide (Brownlee et al., 2005). Although it occurs in other brown algae, kelps are unique because of their large size and ability to grow in thick beds. This allows the resource to be very accessible, since a large biomass can be harvested for an alginate extraction facility.

Alginate's most useful property is its ability to form gels. Its used on industrial scales in a variety of industries including the processed food industry, textile industry, pharmaceutical industry, dental and medical fields, cosmetic industry, and many others, as research is always being conducted on how to bring new, innovative products to market using this versatile component. Some of the things that alginates are used for are emulsifiers, firming agents, flavor enhancers, flavor adjuvant, formulation aid, processing aid, stabilizer, thickener, surface-active agent, and texturizer (Truong et al., 1995). Alginate is used in the textile industry to aid in the dying of fibers and the process of printing onto materials. In the paper industry, it is added to the pulp mixture which improves the paper's smoothness, aids in ink adherence, and helps resist crumpling. It stabilizes colors in paints and dyes and is used in the manufacturing of welding rods. In medical fields, alginates are used to make dental impressions, and are common components to pharmaceutical products. In addition, various fibers can be made with alginates, and their uses include wound dressings, facial masks, fire protective cloth, and static proof cloth (Zhang, 2018). Alginate in its numerous forms will continue to be involved with the many facets of modern society as researchers continue to find new ways to incorporate its useful properties.

The most common form of alginate is extracted as Sodium alginate, although other chemical forms of alginate are available including propylene glycol alginate (PGA), potassium alginate, calcium alginate, and ammonium alginate (Zhang, 2018). The basic steps of extraction follow very similarly, with small changes in order to arrive at the desired form of alginate. Figure 9 below shows the steps taken to extract sodium alginate via two different pathways, the calcium alginate process and the alginic acid process (Hernández-Carmona et al., 1998). Both processes begin with wet, chopped seaweed to which sodium carbonate solution is mixed in. This dissolves the alginate into solution, and the residual solids are strained out. To get the alginate out of the solution, either calcium chloride or an acid is added, depending on which process is being used. The calcium chloride reacts to form fibers of calcium alginate, which can be strained out of solution. To remove the calcium, an acid is added to displace the calcium cations, forming alginic acid fibers. Sodium carbonate is added to form sodium alginate. For the alginic acid process, an acid is added to the original sodium alginate solution. This forms an alginic acid gel that can be strained out the solution. Sodium carbonate is added to the alginic acid gel, which then forms sodium alginate. Sodium alginate is commonly sold in powdered or pelletized form.

Alginate is not the only useful compound contained in Laminariales as there are several other chemicals that are actively extracted from kelps. Kelps commonly contain, in varying degrees, compounds such as phlorotannin, fucoidan, mannitol, and laminarin. All these compounds have useful properties, especially for pharmaceutical applications (see Table 2).

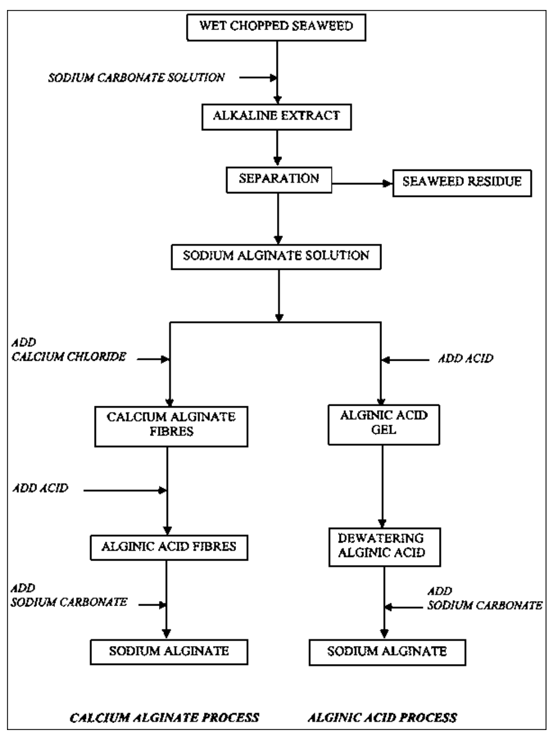


Figure 11: Flow chart displaying the steps required to produce sodium alginate from brown algae via two different methods. Flow chart from Hernández-Carmona et al., 1998.

Biomaterial	Applications
Alginate	Drug delivery, wound healing, heavy metal sequestration, gelling agent
Phlorotannin	Antioxidant, anticancer agent, antidiabetic, anti-HIV agent, anti-allergic agent
Fucoidan	Anticoagulant and antithrombotic agent, antiviral agent, antitumor agent, antioxidant, anti-inflammatory
Mannitol	Bio-fuel feedstock
Laminarin	Anticancer agent, anti-microbial agent, antioxidant, biofuel feedstock

Table 2: Common chemicals found in kelps with their useful applications. Data from Zhang et al., 2020. For more references for specific applications, refer to referenced article.

Biorefinery Model

The presence of these useful compounds, and the developing methods for extracting them, are important for application of a biorefinery model for processing kelp. A kelp biorefinery process would extract a number of useful and valuable components of kelp, and as a result, would decrease the amount of waste that is generated and increase the number of products at the end of the process and making the end result more economically feasible. A current and popular component of the conversation surrounding kelp is the possibility of generating biomass feedstock to produce biogas or other biofuels. Kelps are attractive for this application because they have a significant proportion of polysaccharides that would serve as the primary energy source. Additionally, kelps lack the structural component of lignin, which is utilized by land plants, and generally make them more difficult to break down (Zhang et al., 2020).

Additionally, kelps do not require any freshwater or arable land, which gives kelp biomass a significant advantage over other sources of biomass for biofuel like corn, soybeans, or sugarcane. However, a serious disadvantage to generating biofuel with kelp is the negative net-energy balance, meaning that it takes more invested energy to produce a smaller amount of energy contained by the biofuel (Clarens et al., 2010). The result is that biofuel can be produced using algal biomass, but at a net loss of total energy. This reality necessitates additional products to allow the processing of algal biomass to be economical.

The following diagram (Figure 10) shows the process of applying a biorefinery model to extract pigments, mannitol, phlorotannins, and alginate from kelp biomass. These compounds would first be removed from the kelp, leaving a residual mass that can then be fed into a bioreactor for the generation of biofuel. This process reduces waste and increases the number of marketable products from the same processed kelp biomass.

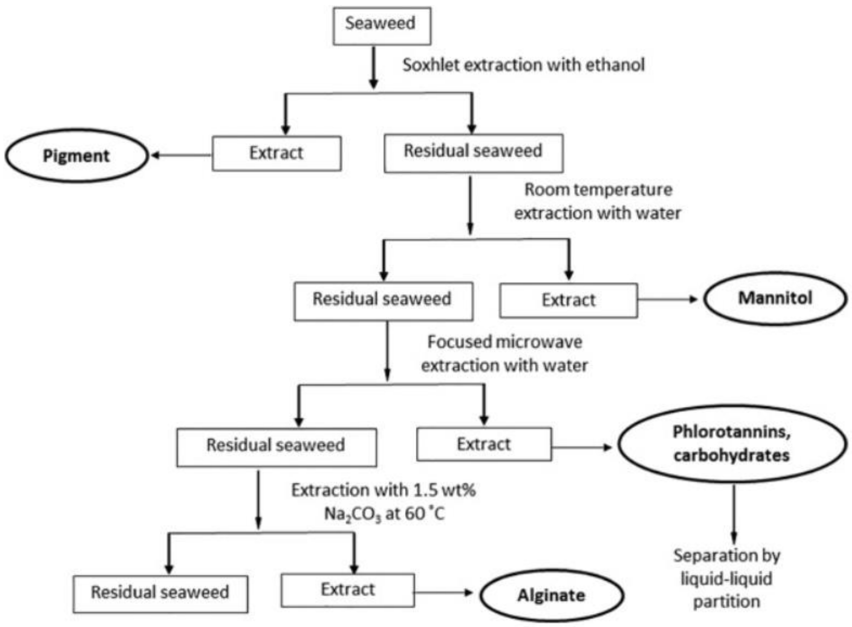


Figure 12: Biorefinery model for extracting valuable compounds from kelp tissue. Diagram from Zhang et al., 2020.

The extraction, marketing, and utilization of these additional compounds will help to create an ecosystem of sorts for the use of kelp-derived products from farmed kelp species. Such an ecosystem is well established in East Asian countries, but anything of the sort needs substantial support in the West.

Kelp and Renewable Energy Sources

Kelp could be an important component of the world's economy as cultivation practices expand around the globe. However, numerous factors are involved while evaluating the impact that large scale kelp cultivation will have at its numerous steps of production. One significant concern is the amount of energy required in the preparation, maintenance, harvesting, and processing for a large-scale kelp farm. Consuming energy produced by fossil fuels in the course of producing kelp for any application could significantly offset the benefits of using kelp. The ideal scenario would be to utilize a renewable source of energy during production of kelp. This way, the two renewable sources could work synergistically, as the world works towards a decarbonized state.

With the exception of the United States of America, all major kelp producing countries have signed the Paris Agreement, promising to work towards reducing the carbon emissions of their countries. Country's investments into renewable energy varies in extent and forms. Additionally, depending on the source of renewable energy, generated renewable energy may not be available to activities related to kelp production. The following paragraphs will describe an overview of renewable energy production in each major kelp producing country.

China

China is of particular interest in this conversation because it is responsible for more than 20% of the world's total carbon emissions, and they also produce most of the kelp in the world. The energy invested in processing kelp, everything from the primary processing to hydrocolloid extraction to other advanced uses for it, is significant. If all kelp were to be processed solely with renewable energy, the greatest impact to the world would come from China, simply because they are growing, processing, and marketing incredible volumes of kelp.

China is actively growing their renewable energy resources. In fact, they are the world's leader in the manufacturing and deployment of wind and solar energy production plants. Of all the solar panel manufacturing companies in the world, China has the six largest, as well as the largest manufacturing company of wind turbines (Slezak, 2017). However, this heavy investment comes with substantial reasoning. A study by the Asian Development Bank found that 7 out of 10 of the world's most polluted cities were in China (Staedter, 2013). This reality has pushed China's government to make drastic investments into cleaner sources of energy to slacken the country's reliance on fossil fuels, and especially coal. Before the push for renewables, China had nearly exclusively generated all of its power for its enormous populous with coal-fired power plants. Since 2011, China has burned more coal than all other countries combined (O'Meara, 2020). In 2019, China produced about 9% of its power from wind and solar sources (Hove, 2020).

Energy generated from renewable sources cannot always be utilized by the kelp industry. Although there are several offshore wind farms, the bulk of wind and solar energy that is generated in China is produced in remote providences in the western portion of the country, such as the Tibetan Plateau. These regions are very dry with little cloud cover, making them very suitable for solar power generation. Additionally, the landscape is quite flat with little to block the path of wind, making these area's suitable for wind farms as well. However, the kelp farms are located on China's eastern coast, far away from the abundance of power generated by solar panels and wind turbines. One significant roadblock for renewable energy in China is the lack of high-voltage transfer infrastructure which prevents energy generated in remote locations from reaching the main power grid where it can be used in population centers. This inability to transfer renewable power has led to the waste of more than 1.75 TWh of wind energy (Reuters, 2015). This reality shows that China has the technology to generate large amounts of energy from renewable sources, but still has obstacles to overcome before they more completely utilize their current potential.

South Korea

South Korea is the world's second largest producer of kelp, and thusly consumes a significant amount of energy in the processing and packaging of kelp products. The country is extremely reliant on fossil fuels to supply energy to their power grid and have very limited capabilities of generating power through renewable resources. South Korea is among the top countries for the importation of both liquified natural gas and coal, and the burning of fossil fuels represents around 69% of the country's generated electricity (EIA, 2020). South Korea has set ambitious goals as a signing member of the Paris Agreement, and has promised funds dedicated to increasing the proportion of renewable energy within their country. Already, reductions to emissions are happening, as in 2014, the burning to fossil fuels produced 83.9% of the country's electricity (KEEI, 2016). As of 2016, South Korea's current renewable energy production sits about at 4.54%, but the government has announced that 20% of the country's energy will come from renewable sources by 2030 (KNREC, 2016). Government incentives have been issued to promote the development of the necessary infrastructure needed to reach that goal. New projects for solar, onshore wind, offshore wind, geothermal, and biomass burning are all be evaluated for their feasibility for power generation. The largest proportion of renewable energy is projected to come from wind power.

The kelp industry could benefit from wind power generation, due to its proximity to the coast. Offshore wind farms could be introduced in areas unsuitable for kelp cultivation, and the generated power could be supplied to kelp processing plants, kelp seedling nurseries, and the surrounding infrastructure necessary for kelp production. Biomass burning seems to be a favorite alternative in the short term due to its low costs and the fact that little needs to be done to modify coal burning power plants to accept biomass sources. However, there are several problems with biomass energy that must be addressed in order to make it sustainable. The main concern stems from the source of the biomass, whether its forest residue associated with deforestation, or a crop that is grown and harvested dedicated for energy production, which will be competing with crops for human and animal feed for arable land and water resources. Developments in technology to allow for the use of kelp biomass for energy production would help solve many of these problems.

Japan

Japan has sourced energy for electricity generation from several sources in the last few decades. Like many other nations, the majority of energy produced is derived from fossil fuels, especially coal, liquified natural gas, and petroleum, which together accounts for about 87% of the country's energy production (ANRE, 2020). In the recent past, a more significant proportion of Japan's energy was derived from nuclear reactors. After the Fukushima Daiichi Accident in March 2011, in which a 15m tsunami caused by an earthquake hit the nuclear power plant and caused the melt down of three reactors, Japan's use of nuclear reactors was essentially halted. Japan underwent a more than 14-fold reduction in nuclear power generation, and went from producing 29% of power from nuclear reactors in 2010 to just 2% in 2012. However, after an extended period of safety inspections, more of Japan's reactors are beginning to come back into action. Currently, about 17% of Japan's energy needs are supplied with renewable energy sources and has pledged to increase that to 22-24% by 2030 (WSA, 2020).

Due to the archipelago that makes up the country of Japan, kelp cultivation areas are relatively close to areas where renewable energy is harvested. The largest island in Japan, Honshu, is only 230 km at its widest point, meaning that renewable energy should always be available around its extensive coastline. Recent increases to efforts to expand renewable resources have been disproportionately focused around solar energy, although wind power will need to be expanded to reach Japan's goal or 22-24% renewable by 2030 (Yamazaki, 2018).

European Union

As aforementioned, there are several countries in the EU with strong and growing interests in kelp aquaculture for one or several of its numerous applications. While East Asian countries are more focused on kelp as a source of human or animal feed, countries in the EU are generally more interested in what can be extracted from kelp. Eating kelp is growing in popularity but is still a niche market compared to the popularity experienced by kelp in East Asian countries.

However, processing kelp for the extraction of its components has significant energy demands, as well as a great deal of fresh water. In the coming years where more renewable energy will be needed, and fresh water in short supply, countries and companies must be prepared to adapt to less than ideal conditions while utilizing an important resource.

The European Union has been on the forefront of efforts to decarbonize modern society, and those efforts should integrate well with processing kelp as kelp mariculture becomes more widespread. Across the entire EU as a whole, 18.9% of their gross energy production came from renewable resources in 2018. That figure is up from 9.6% in 2004, showing that renewable energy production has more than doubled in just 14 years (EUROSTAT, 2020). A few countries that are active in pioneering kelp mariculture in the EU are also integral to increasing the proportion of renewable energy they use. 54.6% of all the energy consumed in Sweden is derived from renewable sources, and renewable energy sources represent 36.1% of all energy consumed in Demark.

Norway, although not a member of the European Union, also derives an impressive proportion of its energy from renewable resources. 98% of all the electricity produced in Norway comes from renewable resources. Of all the electricity produced by renewable resources, hydropower represents the largest proportion of production at 96.1%, followed by thermal power and wind power at 2.5% and 1.4%, respectively (MPE, 2016). Although there are other areas than electricity generation that need to be considered when evaluating a country's reliance on fossil fuels, such as the transportation and shipping sector, it remains to be a key component when evaluating the intersection between the kelp industry and the reduction of fossil fuel use. Overall, Norway consumes fossil fuels in other areas, and their CO_2 emissions have increased by 31.2% since 1990 (IEA, 2020). More efforts need to be made to ensure that the kelp industry can thrive in such a way so that it helps solve the problem of climate change instead of contributing to it.

United States of America

Although the kelp industry in the USA is still in development stages, the renewable energy sector is growing and developing right along with it. The United States is creating more infrastructure and working to better utilize alternative power sources. In 2018, the USA generated nearly 765,000 GWh, and when evaluating metrics such as total amount of renewable energy generated, the USA takes second place, with only China utilizing more renewable energy (IRENA, 2018). However, when the proportion of renewable energy to total energy used is surveyed, the USA as a whole ranks much lower. However, 2020 is expected to see record growth in installations of renewable energy facilities, despite the numerous challenges.

However, the USA's large size and numerous power companies means that renewable energy can be captured in remote, sparsely populated areas located in the nation's interior, but have no way of getting to areas where the kelp industry is operating. Alaska and the New England states has the most established kelp industry in the USA, so it would be most pertinent to survey renewable energy projects in these areas.

New England states are characterized by large population centers and extensive developments along the coastline. Their high concentration of working waterfront and cool water temperatures makes it an ideal location for kelp mariculture, and there are several viable options for the implementation of infrastructure for renewable energy capture. The first offshore windfarm to ever be built in the USA was constructed in coastal waters of Rhode Island in 2016, a facility that produces 30 MWh per year (https://us.orsted.com/wind-projects). Although its capacity is small, Rhode Island was able to establish a precedent on which other New England States can follow. Currently, there are several projects underway that will increase the production of clean energy from offshore wind farms that are several times larger than the first windfarm in Rhode Island. Massachusetts has two proposed projects that, when completed, will produce over 800 MWh of power each (https://www.vineyardwind.com/, https://www.mayflowerwind.com/). Maine, the state that grows the most kelp in the New England states, does not have any plans for offshore wind, but instead are looking to incorporate renewable energy from other sources. Hydroelectric power generates around 31% of Maine's electricity, and land-based wind power provided an additional 24% of generated power (EIA Maine, 2020). These are only a few examples of the New England States efforts to move towards renewable energy sources. The continued development of these projects will ensure the that budding kelp industry in the area will be able to utilize renewable resources in order to keep environmental impacts low.

Alaska does not have the population centers that are widespread in the New England states and, as such, has very different energy needs. Although it's the largest state by landmass, it has the lowest population density. The state features tiny population centers separated from one another by long distances and rugged geographic features. These realities make any kind of standardized, state-wide power grid as employed in the continuous 48 states an impossibility. Due to the discontinuities between communities, independent petroleum powered generators are ideal. Where possible, hydroelectric dams are also utilized to provide the needed electricity to a community. About 30% of electricity is generated from renewable resources in the state, and hydroelectric facilities account for most of that energy, with a few minor wind fields providing some electricity as well (EIA Alaska, 2020).

Additional renewable resources should be evaluated to best incorporate renewable energy sources with the processing and other needs of the burgeoning kelp industry. Areas with abundant rainfall should be ideally set up for hydroelectric facilities. Wind farms could be utilized in areas with sufficient wind speeds. The extreme tides that occur along the coast could be harnessed for tidal power production. All sources of renewable energy should be evaluated to determine the ideal power source for each region.

Gene Flow

Gene flow has been documented for both *S. japonica* and *U. pinnatifida* between farmed populations and wild populations. Using microsatellite markers, evidence of genetic connectivity became clear. Wild may not be the best word to describe "not farmed" populations of *S. japonica* in China because the species as a whole was believed to be introduced from Japan in the 1920's. A genetic analysis between individuals of *S. japonica* from China and Japan showed evidence of founder's effect for the populations in China, which will limit the maximum amount of genetic diversity that is possible (Shan et al., 2017). When genetics of wild and farmed populations of *S. japonica* were compared, the evidence provided by ten microsatellite markers suggested that gene flow was occurring, and that farmed populations had a higher level of genetic diversity than the "wild" populations. Even though gene flow was occurring, genes did not seem to be exchanged at an equal rate. Evidence suggested that the wild populations passed more of their genes to the farmed populations than vice versa (Shan et al., 2017). A very similar situation was seen with wild and farmed populations of *U. pinnatifida*, that wild populations were more likely to spread their genes into farmed populations (Shan et al., 2018). This demonstrates that if a kelp is being cultivated in the natural range of its wild counterparts during a reproductively active season, gene flow is inevitable, and the genetics of both the farmed and wild populations will change. Research must be conducted to evaluate the long term affects of the exchanges, as well as attempt to prevent the mutual contamination of both gene pools.

Climate Change Considerations

Kelp aquaculture is often brought up in conversations surrounding climate change. Anthropogenic activities have raised the concentration of CO_2 and other greenhouse gasses within Earth's atmosphere. These significant alterations to global conditions have been suggested to contribute to several widespread phenomena such as ocean acidification, a global rise in average temperatures, an increased frequency of harmful algal blooms (HABs), and an increased frequency of severe storm events.

Kelp could be an important component in helping to alleviate many of the problems associated with the changing climate. All kelps are primary producers, meaning that they consume CO_2 while growing in a similar way that land plants do. Additionally, kelps take up excess nutrients in the water column that could contribute to eutrophication events and HABs. Studies from Connecticut should that *S. latissima* could remove 38-180 kg of nitrogen hectare^{-1} from nearshore waters (Kim et al., 2015). In China's nearshore aquaculture zones, several studies have shown that cultivating another type of algae, *G. lemaneiformis and P. yezoensis*, has significantly reduced the prevalence of HABs (Wu et al., 2015, Yang et al., 2015). It has also been hypothesized that kelp cultivation could create a "halo effect" of alkalinization. The reduced acidity of the water around kelp farms would be beneficial to shell forming organisms in the vicinity (Ling et al., 2020). Although the scale at which the reduction of acidity is still being evaluated, several factors like weather conditions, wave action, and current speeds would all affect the extent of which a kelp farm could deacidify an area.

Climate change is raising the average temperatures seen all over the world, including its oceans. Since most of the kelp in the world is farmed in the ocean, these rising temperatures are impacting their habitat, and thusly, is affecting where kelps can be grown. This poses a significant problem for the world's top kelp producing countries: China, the Koreas, and Japan. These countries are on the edge of temperate and tropical zones. As the world's oceans get warmer and warmer, the countries that produce nearly all of the world's kelp are at risk of losing hospitable habitat for their aquatic crops to heat stress, as the cooler water temperatures kelp need to thrive in will only be found at higher latitudes.

In the preparations made to adapt to a warmer ocean, governments involved with kelp production are looking to develop heat resistant strains of kelp that can be deployed in warmer waters than that which would be found in natural populations (Hwang et al., 2019). In each of the breeding programs of eastern Asian countries, developing heat resistant cultivars has been identified as a top priority for the future kelp industry. Other options may be to move to more hospitable waters towards the poles, although that could be complicated by Exclusive Economy Zones. Technology is currently being developed that utilizes drones to move kelp farms up and down in the water column with the hopes of increasing growth by cycling between getting enough light during the day and going to the nutrient-rich waters found at depth during the night. Perhaps this same technology to be utilized to move kelp farms according to the temperature of water that it is in to keep the kelp farms in suitable areas (Kim et al., 2019).

Finally, countries access to more northern latitudes that are interested in growing kelp should anticipate a change in the market as countries adapt to the changing climate. Countries that traditionally have provided significant proportions of raw products may not be able to grow the same amounts as they had historically. Countries with cool, nutrient-rich waters, where the effects of climate change will not be manifested till later, could expand their industries locally to make up for the lack of kelp biomass on the global market.

Conclusion

Around the world, the significance of kelp is often overlooked. The most common place an average person interacts with kelp in their day to day lives is probably walking past it on the beach where it washed up during a recent storm. In reality, kelps are invaluable to the ecosystems they occupy and help create and continue to become more and more valuable to humans. With the global population set to reach nine billion people by the midcentury, kelp is quickly becoming more integral to the entire population. Conventional farming practices will be unable to feed everyone, and most capture fisheries are either at capacity or are overfished. Aquaculture will be part of the solution.

Kelp biomass has the versatility that will be needed for the uncertain future ahead. Kelp exists in a variety of ways for food for humans. It can be eaten fresh or cooked, dried or salted. It can be ground and included in processed foods to improve a product’s nutritional quality. Kelp biomass is also a good source of feed for a variety of animals, including those in aquaculture and conventional agriculture. Animals in aquaculture like sea cucumbers, sea urchins, and abalone would eat kelp in their natural environment, making it an obvious choice for sourcing feed. Kelp meal is also included in food formulas for commercial finfish and shrimp feed. The kelp meal provides important macro- and micronutrients and protein, providing the critical nutritional needs for these valuable sources of food and income the human populace.

The industrial uses for kelp are also expansive and growing. Kelp produces a number of useful chemicals that are commonly extracted for applications ranging from the medical field to the food industry. Alginate is perhaps the most common of these chemicals and is used in the production of textiles, welding rods, and gelatinous foods. Applications for these chemicals are actively studied and new uses will continue to be discovered.

Kelp cultivation is concentrated in eastern Asia, and especially China. China, North and South Korea, and Japan account for more than 99% of all the kelp grown in the world. However, efforts elsewhere in the world are growing. Several countries in Europe are looking to grow a few species of kelp, and interest is growing in the United States. Asian countries have used a head start to cement themselves in a leading role in the development of the industry, but other countries can use what they have learned to advance their regional industries. In addition, it is difficult to prepare for the changes that will result from the changing climate. Warming ocean temperatures and changes to the chemical equilibrium of the ocean could alter the locations traditionally used for kelp cultivation, which could lead to major shifts in the production of kelp and kelp products.

Research and development efforts should be invested in making kelp production more efficient and to utilize renewable energy sources to a greater extent. The renewable resources in each region is unique and incorporating them into kelp production efforts will require specialized tailoring in each situation. Using renewable energy to produce this valuable resource will simultaneously remove carbon from the global cycle while not contributing more greenhouse gases to the atmosphere. Additional focused efforts will be required to maximize the effectiveness of this synergistic relationship.

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